EXPLORING ACCRETION AND DISK-JET CONNECTIONS IN THE LLAGN M81*

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ABSTRACT

We report on a year-long effort to monitor the central supermassive black hole in M81 in the X-ray and radio bands. Using *Chandra* and the VLA, we obtained quasi-simultaneous observations of M81* on seven occasions during 2006. The X-ray and radio luminosity of M81* are not strongly correlated on the approximately 20-day sampling timescale of our observations, which is commensurate with viscous timescales in the inner flow and orbital timecales in a radially-truncated disk. This suggests that short-term variations in black hole activity may not be rigidly governed by the "fundamental plane", but rather adhere to the plane in a time-averaged sense. Fits to the X-ray spectra of M81* with bremsstrahlung models give temperatures that are inconsistent with the outer regions of very simple advection-dominated inflows. However, our results are consistent with the X-ray emission originating in a transition region where a truncated disk and advective flow may overlap. We discuss our results in the context of models for black holes accreting at small fractions of their Eddington limit, and the fundamental plane of black hole accretion.

1. INTRODUCTION

Low-luminosity active galactic nuclei (LLAGN) are potentially important transition objects, harboring supermassive black holes that accrete at a rate that is intermediate between Seyfert AGN and quasars, and extremely under-luminous sources such as Sgr A*. LLAGN may provide clues to jet production: in these systems, compact relativistic radio jets are often detected (Nagar et al. 2002, Anderson & Ulvestad 2005), and the natural time scales are such that the details of jet production can be revealed. Moreover, LLAGN are often "radio-loud" (Ho 2008), meaning that jets are an important part of the overall accretion flow. At a distance of only 3.6 Mpc (Freedman et al. 1994), the accreting supermassive black hole at the center of M81 powers the nearest LLAGN, M81*.

The nature of the innermost accretion flow in LLAGN is not clear. It is likely that these sources are still fueled partially by an accretion disk - double-peaked optical emission lines are seen in M81* (Bower et al. 1996; also see Devereux & Shearer 2007) - but relativistic X-ray lines from the inner accretion disk are not clearly detected in these systems (e.g. Dewangan et al. 2004, Reynolds et al. 2009; for a review, see Miller 2007). The inner disk may be truncated, and the innermost flow may be advection–dominated (Narayan & Yi 1994; also see Blandford & Begelman 1999). Theoretical work suggests that thick advective disks and radial flows may help to maintain poloidal magnetic fields and power jets (e.g. Livio 2000; Meier 2001; Reynolds, Garofalo, & Begelman 2006). X-ray observations can test and refine models for advective inflow at low mass accretion rates in a variety of ways. For instance, the inner accretion flow is predicted be extremely hot, with temperatures ranging between 10^{12} K centrally to 10^{9-10} K in their outermost radii (Narayan & Yi 1994, 1995). Recent observations of X-ray binaries have achieved the sensitivity required to test these predictions (e.g. Bradley et al. 2007), and find emission consistent with much lower temperatures.

X-ray emission is often used as a trace of the accretion inflow (although some X-ray emission could originate in a jet; e.g. Markoff, Falcke, & Fender 2001; also see Miller et al. 2002, Russell et al. 2010), and radio emission is used to trace the jet power. In X-ray binaries, X-ray and radio emission follows the relationship $L_R \propto L_X^{0.7}$, both in ensemble and in individual sources (Gallo, Fender, & Pooley 2003; however, see Jonker et al. 2009). This relation has been generalized into a fundamental plane of black hole accretion, combining radio luminosity, X-ray luminosity, and black hole mass (Merloni, Heinz, & Di Matteo 2003; Falcke, Kording, & Markoff 2004; Gultekin et al. 2009). If accretion physics scales predictably with black hole mass, then for any individual object of known mass, the relationship between radio and X-ray emission should be fixed, on average.

Prior to discrete jet ejection events in stellar-mass black holes, quasi-periodic oscillations (QPOs) are often observed in the X-ray flux, with a characteristic frequency of ~ 6 Hz (see, e.g., Nespoli et al. 2003, Ferreira et al. 2006, Klein-Wolt & van der Klis 2008, Fender, Homan, & Belloni 2009). If this frequency is a Keplerian orbital ferequency, it corresponds to a radius of 66 GM/c^2 for a black hole with a mass of 10 M$_\odot$. This radius is broadly consistent with lower limits on the inner edge of the accretion disk in M81* based on the width of the Fe Kα emission line (Dewangan et al. 2004, Young et al. 2007). In stellar mass systems, it is not possible to test disk-jet connections on the period defined by the QPO, although the oscillation might be tied to jet production. In supermassive black holes, however, this timescale is accessible. For a black hole of 7×10^7 M$_\odot$ like that in M81* (Devereux et al. 2003), monitoring every 2–4 weeks can sample the corresponding timescale.

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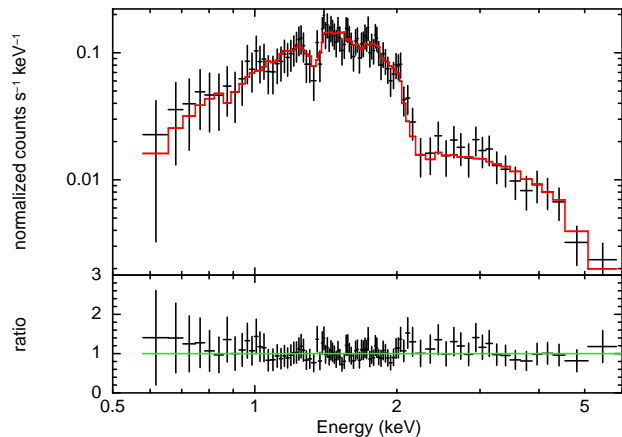[4]National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro NM 87801

FIG. 1.— The plot above shows the combined MEG spectrum of M81* obtained on MJD 53944. The data are acceptably fit using a simple power-law function with a photon index of $\Gamma = 1.70 \pm 0.07$ (shown in red). The lower panel shows the ratio of the observed spectrum to the power-law model.

FIG. 2.— The plot above shows the evolution of 0.5–10.0 keV X-ray flux, X-ray photon index, and 8.4 GHz radio flux density observed in M81* with time. The X-ray flux is plotted in units of 10^{-11} erg cm^{-2} s^{-1}. The radio flux density is plotted in units of 100 mJy. The errors shown on all quantities are 1σ errors; the flux density errors are smaller than the plotting symbols.

In this paper, we present contemporaneous X-ray and radio observations of M81* made using *Chandra* and the VLA, with visits separated by approximately 20 days. The observations and data reduction methods are described in Section 2. Our analysis and results are presented in Section 3. We do not find a clear correlation between radio and X-ray emission in M81*, though a small number of simultaneous points were obtained and span a factor of approximately two in X-ray flux. These results are discussed in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

We observed M81* on ten occasions using *Chandra*. Each observation achieved a total exposure of approximately 15 ksec (see Table 1). In order to minimize photon pile-up in the zeroth order ACIS image, the HETGS was inserted into the light path in each case. The ACIS chips were operated in "FAINT" mode.

We used CIAO version 4.0.2 in processing the *Chandra* data. First-order dispersed spectra from the MEG and HEG were split from the standard "pha2" file, and associated instrument response files were constructed. The first-order MEG spectra and responses were then added using the CIAO tool "add_grating_spectra"; the first-order HEG spectra and responses were added in the same way. The zeroth-order ACIS spectra and responses were generated using the CIAO tool "psextract". In each case, a circular region was used to extract the source flux and a radially–offset annular region was used to extract the background flux. All spectra were grouped to require at least 20 counts per bin using the FTOOL "grppha", in order to ensure the validity of χ^2 statistics.

The VLA also observed M81* on ten occasions (see Table 1). Useful data were obtained on seven occasions that coincide with the *Chandra* X-ray observations. All observations were obtained at 8.4 GHz. The first three coincident exposures were obtained in the "A" configuration (achieving a typical angular resolution of approximately 0.3"), while the last four were obtained in the "B" configuration (achieving a typical angular resolution of approximately 1"). Standard compact calibrator sources were used to calibrate phase and amplitude variations, and to set the overall amplitude scale. The average flux density measured in each exposure is reported in Table 1.
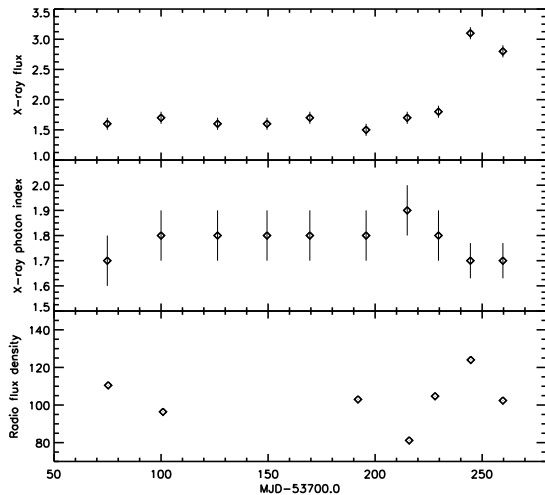
3. ANALYSIS AND RESULTS

The *Chandra* X-ray spectra were analyzed using XSPEC version 12.4 (Arnaud 1996). Spectral fits were made in the 0.5–10.0 keV band. All of the errors reported in this work are 1σ confidence errors. In calculating luminosity values, distances were assumed to be absolute, and uncertainties in luminosity were derived from the flux uncertainties.

We initially made separate fits to the zeroth-order, combined MEG, and combined HEG spectra. In all direct fits, the equivalent neutral hydrogen column density drifted towards zero, which is unphysical. A value of 4.1×10^{20} cm^{-2} is expected along this line of sight (Dickey & Lockman 1990), but this value is too low to be constrained directly in the MEG spectra obtained. For consistency, then, the expected value was fixed in all fits. All of the spectra were acceptably fit ($\chi^2/\nu \leq 1.0$, where ν is the number of degrees of freedom in the fit) with a simple power-law model (see Figure 1). The spectrum of M81* is likely more complex, mostly owing to local diffuse emission (Young et al. 2007), but a simple power-law is an acceptable fit to the modest spectra obtained in our observations.

The zeroth-order spectra suffer from photon pile-up, and are not robust. Particularly in the last two *Chandra* observations, where the flux is higher, the best-fit power-law photon index was found to be harder. This is consistent with multiple low-energy X-rays being detected as single high energy photons. Moreover, the data/model ratio in each spectrum shows an increasing positive trend with energy. The HEG spectra contain many fewer photons than the MEG spectra, and were found to be of little help in constraning the souce flux or spectral index. We therefore restriced our flux analysis to the combined first-order MEG spectra. The second spectrum listed in Table 1, for instance, has just over 2800 photons, and the penultimate spectrum has 4900 photons.

The results of our spectral analysis of each observation are detailed in Table 1. Figure 2 shows the time evolution of the X-ray flux, X-ray power-law photon index, and radio flux density. Between MJD 53900.0 and MJD 53950.0, the X-ray flux
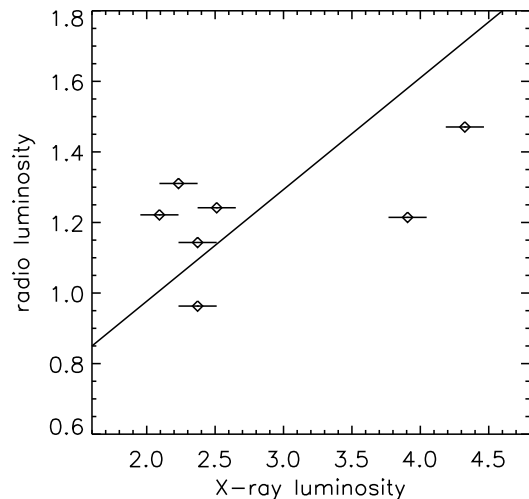
FIG. 3.— The 8.4 GHz radio luminosity of M81* (in units of 10^{37} erg/s) is plotted against its 0.3–10.0 keV X-ray flux (in units of 10^{40} erg/s) in the figure above. The errors shown are 1σ errors; the error on radio luminosity is very small. In spectrally hard black hole sources with jets, a $L_R \propto L_X^{0.7}$ is expected. The solid line above plots $L_R = C \times L_X^{0.7}$, where $C = 6 \times 10^8$ was chosen arbitrarly. The X-ray and radio luminosity values are not significantly correlated.
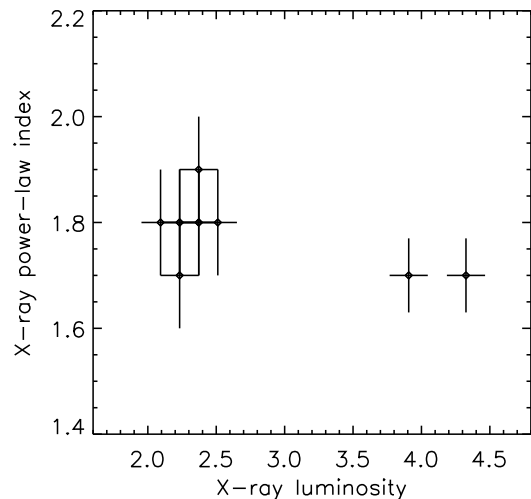
FIG. 4.— The X-ray photon power-law index is plotted versus the 0.3–10.0 keV X-ray luminosity of M81* (in units of 10^{40} erg/s) in the figure above. There is no evidence of the correlations observed in Seyferts and stellar-mass black holes, though a relatively small range in luminosity and spectral index is sampled in our observations.

increases by a factor of approximately two, and the radio flux density increases by slightly less than a factor of two. The X-ray spectral index does not vary significantly during the course of our observations. In each spectrum, the index is consistent with $\Gamma = 1.7$, which is fairly typical of Seyferts (see, e.g., Reynolds 1997) and consistent with prior *Chandra* obsevations of M81* (Young et al. 2007). A power-law is not a unique description of the data; bremsstrahlung models also yield acceptable fits with temperatures of $kT = 5 \pm 2$ keV.

Assuming a flat radio spectrum, we calculated the radio luminosity in the narrow VLA band centered at 8.4 GHz. We also calculated the unabsorbed X-ray flux in the 0.5–10.0 keV band. We assumed a distance of 3.6 Mpc to M81* (Freedman et al. 1994). This radio luminosity is plotted versus X-ray luminosity in Figure 3. The Spearman's rank correlation coefficient for the flux values is 0.23, and it is apparent in Figure 3 that there is no strong correlation between the X-ray and radio luminosity.

In Figure 4, the X-ray power-law photon index is plotted versus the X-ray luminosity. Here again, there is no clear correlation visible in the plot. The Spearman's rank correlation coefficient for these quantities is -0.39, indicating that there is no significant correlation.

The sampling rate of the X-ray light curve is 21 ± 5 days and that of the radio light curve is 19 ± 5 days. Therefore, the radio and X-ray peak around MJD 53944.6 are formally consistent with being simultaneous, and any delay between radio and X-rays is ≤ 20 days. Given the sampling rate, it is likely that the radio/X-ray flare is caused by a factor of ~ 2 change in $\dot{M}$ between MJD 53929–53960.

4. DISCUSSION AND CONCLUSIONS

The nature of the inner accretion flow in LLAGN is not yet clear. It is possible that LLAGN retain many of the characterstics of Seyferts, perhaps including an accretion disk extending to the ISCO (e.g. Herrnstein et al. 1998, Maoz 2007). It is also possible that LLAGN are more like under-luminous sources, such as Sgr. A*, and best described in terms of an ADAF or coupled ADAF-jet system (see, e.g., Nemmen et al. 2010). In this work, we have attempted to explore the the nature of the inner accretion flow in an LLAGN by examining evidence for a disk-jet connection in M81*. Based on observations of QPOs with a frequency of ~ 6 Hz in stellar-mass black holes just prior to jet ejection episodes, we sampled a commensurate timescale in M81*. If this timescale is an orbital period, it implies a radius that is compatible with lower limits on the inner radius of the accretion disk in M81* based on modeling of the Fe Kα emission line detected in deep obsevations of this source ($R \geq 50 - 60 \, GM/c^2$; Dewangan et al. 2004, Young et al. 2007). If the innermost accretion flow is advective, so that it is geometrically thick but retains some viscosity and angular momentum, then our sampling timescale is also commensurate with the viscous timescale in the very innermost region around the black hole (e.g. $6 GM/c^2$). Our monitoring observations improve upon many prior investigations of disk-jet connections in many supermassive and stellar-mass black holes in that our radio and X-ray observations were nearly simultaneous.

At low fractions of the Eddington limit, stellar-mass black holes have hard X-ray spectra (see, e.g., Miller et al. 2006, Miller, Homan, & Miniutti 2006, Tomsick et al. 2008, Reis, Fabian, & Miller 2010; for a review, see Remillard & McClintock 2006) and radio emission that is consistent with a compact jet (Fender, Homan, & Belloni 2009). Both in individual sources and in an ensemble, radio and X-ray emission are related by the expression $L_R \propto L_X^{0.7}$ (Gallo, Fender, & Pooley 2003; see, however, Jonker et al. 2009).

Our data do not strongly confirm nor reject the possibility that M81* regulates its radio and X-ray output according to $L_R \propto L_X^{0.7}$ (see Figure 3). However, it is clear that if M81* does follow this relation, the regulation of its radiation is not rigid on short time scales. Recent work on Sgr A* shows that the source approaches the expected relation when it flares, but otherwise falls below it (Markoff 2005). These outcomes suggest that black holes might generally channel a fixed fraction of the matter inflow (traced by X-ray emission) into a jet (traced by radio emission), but not necessarily at every moment. Said dif-

ferently: the energy channeled into jets at any given time may vary as it is likely to be somewhat stochastic, but on average the expected relationship may hold. In past investigations, scatter in the $L_R \propto L_X^{0.7}$ relation and the fundamental plane (e.g. Gultekin et al. 2009) could plausibly be explained in terms of non-simultaneous X-ray and radio observations; our results suggest a degree of intrinsic scatter.

Within states where compact, steady jets are produced, spectral hardness and luminosity are positively correlated in stellar-mass black holes (e.g. Tomsick et al. 2001; also see Rykoff et al. 2007). Hardening of this kind has also been observed in Sgr A* (Baganoff et al. 2001). In constrast, Seyferts appear to become spectrally softer with higher X-ray luminosity (see Vaughan & Fabian 2004). The X-ray spectrum of M81* does not show a strong trend with luminosity, and we are not able to characterize the variability of M81* as being more like Sgr A* or more typical of Seyferts.

Recent modeling of the broad-band spectrum of M81* suggests that its accretion flow may be very similar to that in the hard state of stellar-mass black holes and Sgr A*. Markoff et al. (2008) showed that the same jet-dominated broad-band accretion flow model can be applied to stellar-mass black holes, Sgr A*, and to M81*. The stellar-mass black hole V404 Cyg may be the source in which X-ray observations permit the best constraints on the inner accretion flow at 10^{-5} $L_{Edd.}$. Recent analysis by Bradley et al. (2007) measure a temperature of $kT \simeq 5$ keV with bremsstrahlung models. This is much too cold for even the outer parts of a simple advection-dominated accretion flow, for which temperatures of $kT \geq 85$ keV are predicted (Narayan & Yi 1995). Similarly, fits to our spectra of M81* with bremsstrahlung models give $kT = 5 \pm 2$ keV. In this sense, then, the X-ray spectrum of M81* is inconsistent with very simple ADAF models because a ~ 5 keV plasma is too cold to be compatible with such models.

On the other hand, Young et al. (2007) showed that a combined 282 ksec *Chandra* spectrum of M81* (essentially at the flux level of the first eight observations presented here) could be described by a model that was dominated by emission from collisional plasma with temperatures ranging from 1–100 keV. In terms of an emission measure analysis, the peak emission came from ≈ 10–30 keV plasma. Similarly, one could construct an ADAF type model where $kT \propto R^{-0.5}$, with emission ranging from ≈ 1–10^4 GM/c^2. The construction of such models, however, relied upon the detection and measurement of plasma emission line features, which are too weak to detect in any of our short, individual observations. (We have verified, however, that the basic line structure reported by Young et al. is unal-

tered in the full, combined 450 ksec spectra.) In principle, if one could associate line variations with the factor > 2 continuum flux level variations shown here, especially for the lower temperature lines that should arise in the less central parts of the system, this would place strong constraints on any ADAF type model.

The large increase in X-ray flux detected in our last two observations occurred on a time scale shorter than two weeks, which corresponds to a light travel distance of $\approx 10^{3.5}$ GM/c^2. This is smaller than the ADAF emission region postulated by Young et al. (2007), which in any case would respond on time scales longer than the light travel time. Thus, any correlated line/continuum changes would alter the simple ADAF assumptions of emission dominated by a hot, optically thin, flow. For example, in a situation where the hot inner flow and thin disk partially overlap, a transition region with a lower temperature may be expected. Transition regions have been treated in some detail in numerous works, including Blandford & Begelman (1999) and Meyer, Liu, and Meyer-Hofmeister et al. (2000). Emission originating in a transition region can potentially explain our spectral and variability results, and those reported by Young et al. (2007). Moreover, this possibility is qualitatively consistent with evidence of thin disks extending to small radii at low Eddington fractions in LLAGNs and LINERS (Maoz 2007) but still allows for a coupled ADAF plus jet system like that described by Nemmen et al. (2010).

Decisive observations may be feasible with the proposed International X-ray Observatory (IXO): a single 30 ksec observation with IXO will achieve a sensitivity greater than that in the combined 282 ksec *Chandra* exposure analyzed by Young et al. (2007). The higher spectral resolution of the calorimeter expected to fly aboard IXO will facilitate both the detection of weak lines and the detection of small velocity shifts. If the innermost accretion flow in M81* is a dynamic environment where X-ray flares help to drive a jet and/or a wind, IXO spectroscopy will be able to detect corresponding variations in the line spectrum discussed by Young et al. (2007). If a weak iron line is produced in the inner disk, the sensitivity of IXO will help to detect and resolve the dynamical information imprinted on any such line.

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TABLE 1

X-ray and Radio Observations

Obs.	T_X (MJD)	Exposure (ksec)	Γ	F_X (10^{-11} erg cm^{-2} s^{-1})	T_R (MJD)	Exposure (ksec)	$S_{8.4}$ (mJy)	Configuration
1	53774.9	15.0	1.7(1)	1.6(1)	53775.3	3.4	110.5(1)	A
2	53800.0	15.0	1.8(1)	1.7(1)	53800.9	5.3	96.4(1)	A
3	53826.4	15.0	1.8(1)	1.6(1)	–	–	–	–
4	53849.5	14.7	1.8(1)	1.6(1)	–	–	–	–
5	53869.5	15.0	1.8(1)	1.7(1)	–	–	–	–
6	53895.8	15.0	1.8(1)	1.5(1)	53892.0	5.2	103.0(1)	A
7	53915.0	14.9	1.9(1)	1.7(1)	53915.9	5.3	81.2(1)	B
8	53929.6	15.1	1.8(1)	1.8(1)	53928.0	5.2	104.7(1)	B
9	53944.5	14.6	1.70(7)	3.1(1)	53944.7	6.3	124.0(1)	B
10	53959.7	15.0	1.70(7)	2.8(1)	53959.7	5.2	102.4(1)	B

NOTE.—The table above lists observation times and properties of the flux observed from M81* through our joint monitoring program. The X-ray spectra were fit with simple absorbed power-law models; the power-law index and resulting 0.5–10.0 kV flux are reported above. The radio flux density at 8.4 GHz is reported from each successful observation with the VLA. All errors are 1σ confidence errors; number in parentheses indicate the error in the last digit.

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